New results on the spectroscopy of X, Y, Z states from LHC experiments

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Abstract

The main results from LHC experiments on XYZ charmonium-like candidates are summarized.

1 Introduction

According to our current understanding, the forces responsible to bind quarks into hadrons are described by the non-Abelian field theory called Quantum Chromodynamics (QCD). In QCD-motivated quark potential models, the quarkonia states are described as a quark-antiquark pair bound by an interquark force with a short- distance behavior that is approximately Coulombic, plus an increasing confining potential that dominates at large separations. In one of the simplest approaches, the energy levels can be determined by solving the corresponding non-relativistic Schrodinger equation in order to obtain the expected masses of the charmonium spectrum, characterized by the radial quantum number n and the relative orbital angular momentum between the quark and the antiquark, L. In particular, all predicted states lying under the $D\bar{D}$ mass threshold have been observed [1–4].

On the other hand, the possible existence of more sophisticated states than mesons and baryons, like the multiquark states, hybrid mesons and mesonic molecules has been discussed since the early days of the quark model [2, 5–8].

In the last decade, considerable experimental evidence has been collected about the existence of new states, lying in the charmonium mass range, but not fitting well the charmonium mass spectrum picture [9–15]. Most of the observations also suggested that these candidates are exotic. These studies have been performed at Babar and Belle, two experiments which took data at the e^+e^- Beauty Factories at SLAC (Stanford Linear Accelerator Center, USA) and KEK (High-Energy Accelerator Research Organization, Japan), respectively. Confirmations have also come from the CDF experiment, collecting data from $p\bar{p}$ interactions at Fermilab,USA.

In these notes the main results from LHC experiments on XYZ charmonium-like candidates are summarized. In Section 1 the main features of the LHCb detector are presented. Section 2 is dedicated to the discussion of the measurements of the X(3872) mass and cross-section in the LHCb and CMS experiments. In Section 4, the results of the search for the X(4140) and X(4274) states in $B^+ \rightarrow K^+ J/\psi\, \phi$ decays at LHCb are presented. The conclusions are presented in Section 5.

2 LHCb and CMS detectors

LHCb is an experiment dedicated to heavy flavour physics at the LHC [16]. Its primary goal is to search for indirect evidence of new physics in CP violation and rare decays of beauty and charm hadrons.
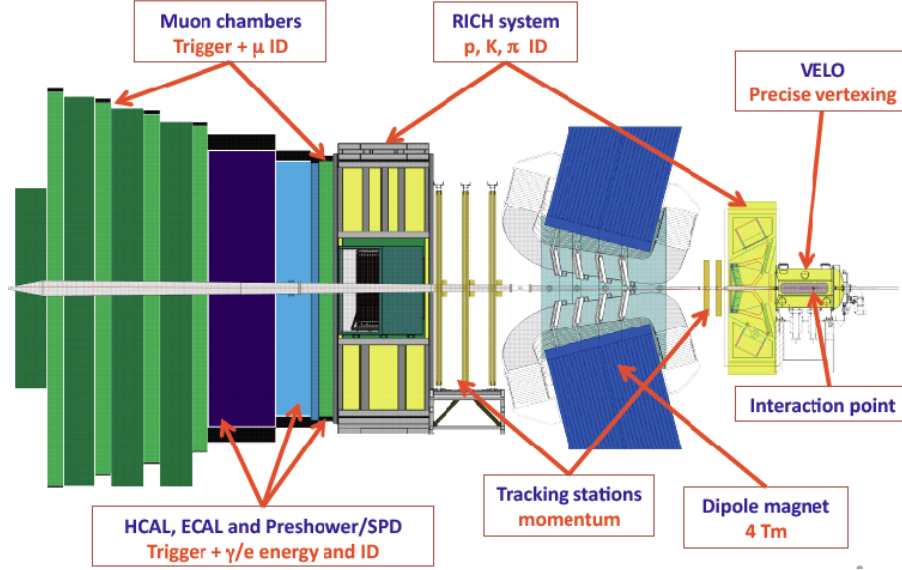
Figure 1: YZ view of the LHCb detector.

LHCb detector is a single-arm spectrometer (see figure 1) with a forward angular coverage from approximately 10 mrad to 300 (250) mrad in the bending (non-bending) plane, corresponding to a pseudorapidity range of $2 < \eta < 5$. In fact, the detector geometry is optimized to cover the region where the $b\bar{b}$ cross-section peaks in such way that, even if just covering about 4% of the solid angle, the LHCb detects about 40% of heavy quark hadrons produced in the proton-proton colisions.

The spectrometer consists of a vertex locator, a warm dipole magnet, a tracking system, two RICH detectors, a calorimeter system and a muon system. The track momenta are measured to a precision of $\delta p/p$ between 0.35% and 0.5%. The Ring Imaging Cherenkov Detector (RICH) system provides excellent charged hadron identification in a momentum range 2-100 GeV/c. The calorimeter system identifies high transverse energy hadron, electron and photon candidates and provides information for the trigger. The muon system provides information for the trigger and muon identification with an efficiency of about 95% for a misidentification rate of about 1-2 % for momenta above 10 GeV/c.

The luminosity for the LHCb experiment can be tuned by changing the beam focus at its interaction point independently from the other interaction points, allowing LHCb to maintain the optimal luminosity in order not to saturate the trigger or to damage the delicate sub-detectors parts. In fact, due this capability, LHCb was able to keep its luminosity at the constant value of $3.5 \times 10^{32} \, \text{cm}^{-2}\text{s}^{-1}$ during most of 2011 data taking.

The trigger chain is composed by a first level hardware trigger and two levels of software triggers. LHCb uses hadrons, muons, electrons and photons throughout the trigger chain, maximizing the trigger efficiency on all heavy quark decays and making the experiment sensitive to many different final states.

In 2010 and 2011, the detector recorded about $1.1\,\mathrm{fb}^{-1}$ integrated luminosity in proton-proton collisions at $\sqrt{s} = 7$ TeV, corresponding to 90% of the luminosity delivered by the Large Hadron Collider(LHC) to LHCb.

The CMS is a multi-purpose experiment at LHC, designed with the main goal of search for new physics phenomena at large transverse momentum scales. CMS cover a rapidity range up to $|\eta| < 2.5$ and since -quark production peaks at large rapidities, CMS is most able to search for charmonium-like candidates produced primary in the proton-proton collisions. For a complete description of the CMS detector see [17].

3 X(3872) mass and cross-section measurements at LHC and CMS

The X(3872) resonance was discovered in 2003 by the Belle collaboration in the $\mathrm{B}^+ \to \mathrm{K}^+\mathrm{X}(3872)$, $\mathrm{X}(3872) \to \mathrm{J}/\psi\,\pi^+\pi^-$ decay chain [18]. Its existence was confirmed by the CDF [19], DØ [20] and BaBar [21] collaborations.

The X(3872) mass is currently known with $< 1.0\,\mathrm{MeV}/c^2$ precision, the dipion mass spectrum in the decay $\mathrm{X}(3872) \to \mathrm{J}/\psi\,\pi^+\pi^-$ [22, 23] has been studied and the X(3872) quantum numbers have been constrained to be either $J^{PC} = 2^{-+}$ or 1^{++} [24] and are still not established. However, despite the cumulated experimental and theoretical effort, the nature of the X(3872) remains uncertain. Among the possible interpretations for this state currently discussed in the literature, one can remark the mesonic molecule, the hybrid meson and the tetraquark hypotesis. The conventional charmonium interpretation is not excluded.

In LHCb the analysis is performed on $34.7\,\mathrm{pb}^{-1}$ dataset collected in 2010 in pp collisions at $\sqrt{s} = 7\,\mathrm{TeV}$. The X(3872) signal has been isolated applying tight cuts in order to reduce the combinatorial background, generated when a correctly reconstructed J/ψ meson is combined with a random $\pi^+\pi^-$ pair from the primary pp interaction. The selection cuts are optimized using reconstructed $\psi(2S) \to \mathrm{J}/\psi\,\pi^+\pi^-$ decays, as well as "same-sign pion" candidates satisfying the same criteria as used for the X(3872) and $\psi(2S)$ selection. A further background suppression is reached applying the requirement Q < 300 MeV/c^2, where $Q = \mathrm{M}_{\mu^+\mu^-\pi^+\pi^-} - \mathrm{M}_{\mu^+\mu^-} - \mathrm{M}_{\pi^+\pi^-}$. See [25]
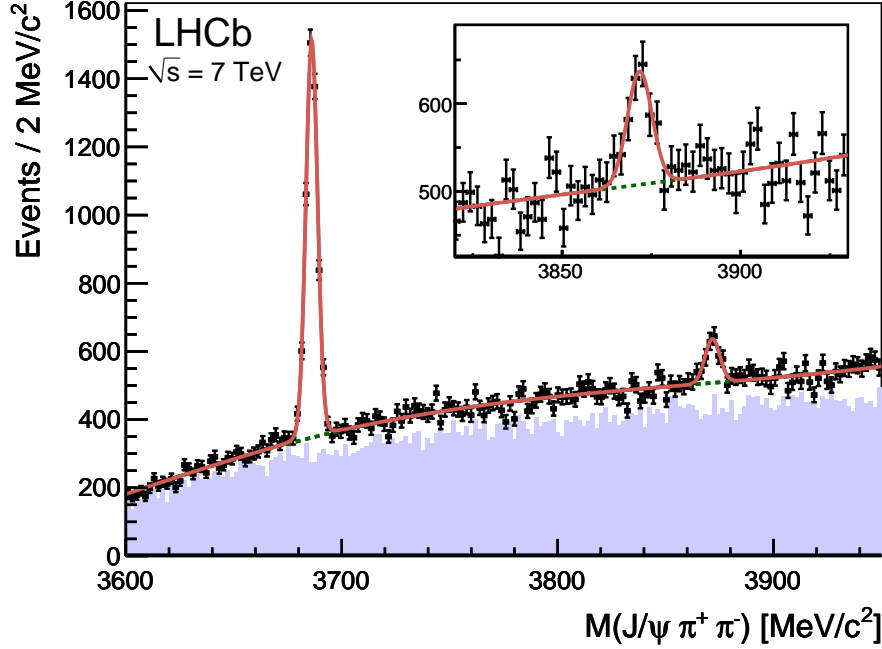
Figure 2: Invariant mass distribution of J/ψ π⁺π⁻(black points with statistical error bars) and same-sign J/ψ π⁺π⁺(blue filled histogram) candidates. The solid red curve is the result of the fit described in the text. The inset shows a zoom of the X(3872) region.

for a detailed discussion on the selection procedure.

The masses of the $\psi(2S)$ and X(3872) mesons are determined from an extended unbinned maximum likelihood fit of the reconstructed $J/\psi \pi^+\pi^-$ mass in the interval $3.60 < M_{J/\psi\pi^+\pi^-} < 3.95\,\mathrm{GeV}/c^2$. The $\psi(2S)$ and X(3872) signals are described with a non-relativistic Breit-Wigner function convolved with a Gaussian resolution function. The intrinsic width of the $\psi(2S)$ is fixed to the PDG value and the X(3872) width is fixed to zero in the nominal fit. The ratio of the mass resolutions for the X(3872) and the $\psi(2S)$ is fixed to the value $\sigma_{X(3872)}/\sigma_{\psi(2S)} = 1.31$. The background shape is described by the functional form $f(M) \propto (M - M_{J/\psi} - 2M_\pi)^{c_0} e^{(-c_1 M - c_2 M^2)}$. The results of the fit are summarized in the table 1.

At LHCb, the same sample used to measure the X(3872) mass has been used to perform X(3872) production studies. The product of the inclusive production cross-section $\sigma(pp \to X(3872) + \cdots)$ and the branching fraction

Fit parameter	$\psi(2S)$	X(3872)
Number of signal events	3998 ± 83	565 ± 62
Mass [MeV/c^2]	3686.10 ± 0.06	3871.88 ± 0.48
Mass resolution [MeV/c^2]	2.54 ± 0.06	3.33 ± 0.08
S/B in $\pm 3\sigma$ window	1.5	0.15
Number of background events	73094 ± 282	$-$

Table 1: Fit results on LHCb X(3872) studies.

$\mathcal{B}(\text{X}(3872) \to \text{J/}\psi\,\pi^+\pi^-)$ is determined according the expression

$$\sigma(\text{pp} \to \text{X}(3872) + \cdots) \times \mathcal{B}(\text{X}(3872) \to \text{J/}\psi\,\pi^+\pi^-) = \frac{\text{N}_{\text{X}(3872)}^{corr}}{\xi \times \mathcal{L}_{\text{int}} \times \mathcal{B}(\text{J/}\psi \to \mu^+\mu^-)}$$

where $\text{N}_{\text{X}(3872)}$ is the efficiency-corrected signal yield, ξ is a correction factor to the simulation-derived efficiency that accounts for known differences between data and simulation, $\mathcal{B}(\text{J/}\psi \to \mu^+\mu^-) = (5.93 \pm 0.06) \times 10^{-2}$ is the J/$\psi \to \mu^+\mu^-$ branching fraction, and $\mathcal{L}_{\text{int}}$ is the integrated luminosity. See [25] for detailed discussion about the calibration procedure and the treatment of the different sources of systematic uncertainty. The studies are performed just considering candidates lying inside the fiducial region for the measurement defined by

$$2.5 < y < 4.5 \text{ and } 5 < p_T < 20\,\text{GeV/}c$$

where y and p_T are the rapidity and transverse momentum of the X(3872). The X(3872) production cross section at LHCb is measured to be

$$\sigma(\text{pp} \to \text{X}(3872) + \cdots) \times \mathcal{B}(\text{X}(3872) \to \text{J/}\psi\,\pi^+\pi^-) = 4.7 \pm 1.1(\text{stat}) \pm 0.7(\text{syst})\,\text{nb}$$

The CMS Collabration also performed studies on the X(3872) production. CMS uses a dataset of $40\,\text{pb}^{-1}$ collected in pp collisions at $\sqrt{s} = 7\,\text{TeV}$ to measure the ratio of the branching fractions of $\psi(2S) \to \text{J/}\psi\ \pi^+\pi^-$ and X(3872) $\to \text{J/}\psi\ \pi^+\pi^-$ which is defined as

$$R = \frac{\sigma(\text{pp} \to \text{X}(3872) + \cdots) \times \mathcal{B}(\text{X}(3872) \to \text{J/}\psi\,\pi^+\pi^-)}{\sigma(\text{pp} \to \text{X}(3872) + \cdots) \times \mathcal{B}(\psi(2S) \to \text{J/}\psi\,\pi^+\pi^-)}$$

inside the fiducial region defined by

$$p_{\text{T}} > 8\,\text{GeV/}c \text{ and } |y| < 2.2$$

.

The result of the CMS analysis is

$$R = 0.087 \pm 0.017(\text{stat}) \pm 0.009(\text{syst}),$$

where the first error refers to the statistical uncertainty and the second error contains the sum of all systematic uncertainties, as described in [26], added in quadrature. See [26] for a detailed discussion of the selection procedure and uncertainties estimation.

4   Search for the X(4140) state in $\mathrm{B^+ \to K^+ J/\psi\,\phi}$ decays

The CDF collaboration has reported a 3.8σ evidence for the $\mathrm{X(4140) \to J/\psi\,\phi}$ state using data collected in proton-antiproton collisions at the Tevatron ($\sqrt{s} = 1.96$ TeV) [27]. In a preliminary update on the analysis [28], the CDF collaboration reported 115 ± 12 $\mathrm{B^+ \to K^+ J/\psi\,\phi}$ events and 19 ± 6 X(4140) candidates with a statistical significance of more than 5σ. The mass and width were determined to be $4143.4^{+2.9}_{-3.0} \pm 0.6 \mathrm{MeV}/c^2$ and $15.3^{10.4}_{-6.1} \pm 2.5$ MeV/c^2, respectively. The relative branching ratio was measured to be $\mathcal{B}(\mathrm{B^+ \to K^+ X(4140)}) \times \mathcal{B}(\mathrm{X(4140) \to J/\psi\,\phi})/\mathcal{B}(\mathrm{B^+ \to K^+ J/\psi\,\phi}) = 0.149 \pm 0.039(\text{stat}) \pm 0.024(\text{syst})$.

Since a charmonium state at this mass is expected to have much larger width because of open flavor decay channels, the decay rate of the $\mathrm{X(4140) \to J/\psi\,\phi}$ mode, so near to kinematic threshold, should be small and unobservable. Due to these issues, the CDF's report rejuvenated the discussions on exotic hadronic states. It was cogitated that the X(4140) resonance could be a molecular state [29–31], a tetraquark state [32, 33], a hybrid state [34, 35] or even a rescattering effect [15, 16].

The CDF data also suggested the presence of a second state, referred here as X(4274) with mass $4274.4^{+8.4}_{-6.4} \pm 1.9$ MeV/c^2 and width $32.3^{+21.9}_{-15.3} \pm 7.6$ MeV/c^2. The corresponding event yield was 22 ± 8 with 3.1σ significance. This observation has also received attention in the literature [36, 37]. On the other hand, the Belle experiment found no evidence for the X(4140) and X(4274) states [38, 39].

The LHCb analysis [40, 41] starts reconstructing a $\mathrm{B^+}$ candidate as five-track ($\mu^+\mu^- \mathrm{K^+ K^- K^+}$) vertex using well reconstructed and identified muons and kaons candidates. The $\mathrm{B^+}$ candidates are required to have $p_T > 4.0$ GeV/c and a decay time of at least 0.25 ps. The invariant mass of the ($\mu^+\mu^- \mathrm{K^+ K^- K^+}$) combination is evaluated after the muon pair is constrained
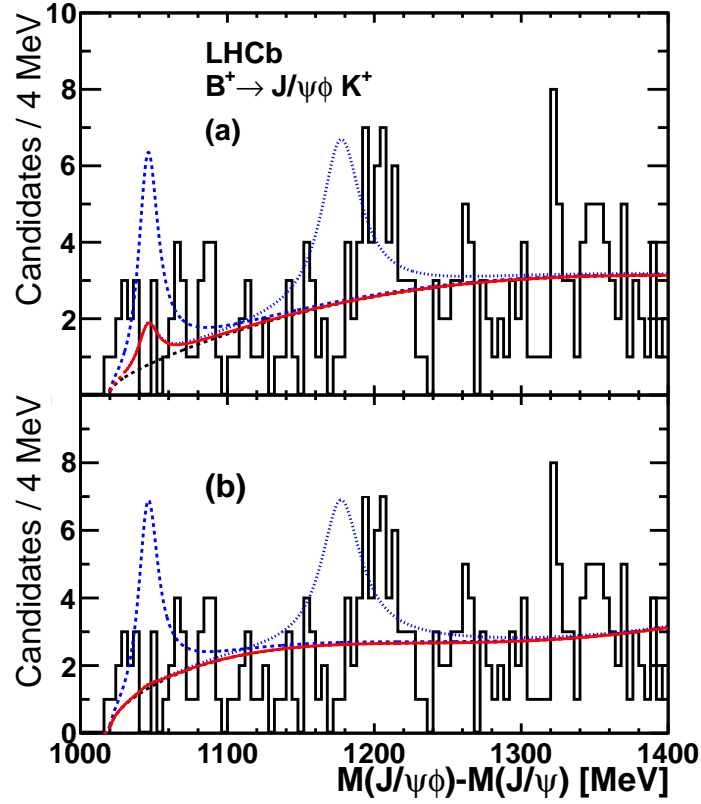
Figure 3: Distribution of the mass difference $M(J/\psi\,\phi) - M(J/\psi)$. Fit of the X(4140) signal on top of a smooth background is superimposed (solid red line). The dashed blue (dotted blue) line on top illustrates the expected X(4140) (X(4274)) signal yield from the CDF measurement. The top and bottom plots differ by the background function (dashed black line) used in the fit: (a) a background efficiency-corrected three-body phase-space; (b) background efficiency-corrected quadratic function.

to the J/ψ mass, and all final state particles are constrained to a common vertex. Further background suppression is provided using the likelihood ratio discriminator method.

The $B^+ \to K^+ J/\psi\,\phi$ invariant mass distribution, with at least one $K^+ K^-$ combination having an invariant mass within ± 15 MeV/c^2 of the nominal ϕ mass was fitted by a Gaussian and a quadratic function resulting in 346 ± 20 B^+ events with a mass resolution of 5.2 ± 0.3 MeV/c^2.

The X(4140) state was searched selecting events within ± 15 MeV/c^2 of the ϕ mass. Figure 3 shows the mass difference $M(J/\psi\,\phi) - M(J/\psi)$ distribution without J/ψ or ϕ mass constraints. No narrow structure is observed near the

threshold. The fit results are $N^{(a)}_{\text{X}(4140)} = 6.9 \pm 4.9$ or $N^{(b)}_{\text{X}(4140)} = 0.6 \pm 7.1$, depending on the background shape used.

The CDF's fit model was used to quantify the compatibility of the two measurements and considering the LHCb $\text{B}^+ \to \text{K}^+ \text{J}/\psi\,\phi$ yield, the efficiency ratio, and the CDF value for $\mathcal{B}(\text{B}^+ \to \text{K}^+ \text{X}(4140))/\mathcal{B}(\text{B}^+ \to \text{K}^+ \text{J}/\psi\,\phi)$, one concludes that LHCb should have observed $35 \pm 9 \pm 6$ events, where the first uncertainty is statistical from the CDF data and the second includes both the CDF and LHCb systematic uncertainties. The LHCb results disagree with the CDF observation by $\sim 2.7\sigma$. In the case of the X(4274) candidate, the same procedure predicts that LHCb should have observed 53 ± 19 X(4274) candidates. The final results are the following upper limits at 90%CL

$$\frac{\mathcal{B}(\text{B}^+ \to \text{K}^+ \text{X}(4140)) \times \mathcal{B}(\text{X}(4140) \to \text{J}/\psi\,\phi)}{\mathcal{B}(\text{B}^+ \to \text{K}^+ \text{J}/\psi\,\phi)} < 0.07,$$

$$\frac{\mathcal{B}(\text{B}^+ \to \text{K}^+ \text{X}(4274)) \times \mathcal{B}(\text{X}(4274) \to \text{J}/\psi\,\phi)}{\mathcal{B}(\text{B}^+ \to \text{K}^+ \text{J}/\psi\,\phi)} < 0.08.$$

5   Conclusions

A selection of results on XYZ states spectroscopy at the LHC have been summarized. Many new results are expected from the analysis of the 2011 and 2012 datasets and as well from the news studies currently on-going.

The LHC experiments are in a privileged position to explore the production mechanisms and spectra of the XYZ states, delivering competitive results in the heavy flavor sector.

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